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13. ABSTRACT (*Maximum 200 words*)

Analytical, numerical, and experimental studies have documented the flow development and surface heat transfer for several three-dimensional end-wall flows, and indicate the presence of highly unsteady vortex formation within the end-wall boundary layer. This vortex formation process leads rapidly to the evolution of three-dimensional separation effects which have a profound influence on the surface heat transfer. Analysis of the three-dimensional behavior indicates the presence of persistent and strong interactions between the end-wall boundary layers on both the surface and the side-wall boundary layers of the obstacle.

A detailed series of Navier-Stokes calculations have been carried out for a vortex-induced motion similar to that encountered in turbulent boundary layers. As the Reynolds number is increased, a new type of instability associated with surface layer separation was found which leads to breakup of the surface layer.

Experimentally, laminar approach flows always develop discrete, periodic necklace vortices in the junction region, whereas a turbulent approach yields a dominant necklace or horseshoe-shaped vortex that moves chaotically. Examinations of the complex fluid/heat transfer processes using PIV and thermochromic liquid crystals shows that these junction vortices undergo very strong surface interactions, which creates strongly focused "eruptions" of surface fluid; these studies show a direct correlation between the eruptive processes and local regions of high heat transfer.

14. SUBJECT TERMS: Particle Image Velocimetry, PIV, Heat Transfer, Junction Flow, Horseshoe Vortices, Boundary Layers, Vortex Dynamics, Laminar Vortices, Turbulent Vortices, Vortex Interactions

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FINAL REPORT
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Heat Transfer and Flow Structure in End-Wall Boundary Layers

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20 August 1997

Executive Summary

Objectives

This research is a combined theoretical, computational and experimental study of the basic physics associated with the development of flow structure in end-wall boundary layers (e.g., wing-body and turbine blade type junctures) and the influence of this flow structure on surface heat transfer. One central objective is to determine the modes of development of juncture flow structures, their temporal behavior, and subsequent interactions with the bounding surfaces. Both laminar and turbulent approach flows are considered in the experimental work; the theoretical/computational work focuses on laminar approach flows. A second objective is to assess the influence of the developing flow structure on temporal surface heat transfer, paying particular attention to the influence of vortex-surface interactions.

Overview

Analytical and numerical studies have documented the flow development and surface heat transfer on the symmetry plane for several three-dimensional end-wall flows. It is found that highly unsteady vortex formation within the end-wall boundary layer is observed. These events lead rapidly to the evolution of three-dimensional separation effects which have a profound influence on the surface heat transfer. Analysis of the three-dimensional behavior indicates the presence of persistent and strong interactions between the end-wall boundary layers on the surface and side-wall boundary layers on the obstacle.

The process of breakup and instability in vortex-induced flows is relevant to the processes that occur in general turbulent boundary layers. A detailed series of Navier-Stokes calculations have been carried out for a vortex-induced motion similar to that encountered in turbulent boundary layers. As the Reynolds number is increased, a new type of instability associated with surface layer separation was found which leads to breakup of the surface layer.

Experimentally, laminar approach flows have been examined thoroughly, with the flow being shown to always develop discrete necklace vortices in the leading edge region; these necklace vortices are observed to evolve through a series of periodic flow regimes as Reynolds number increases. PIV studies have revealed the details of the processes of both vortex-surface interactions, as well as the mechanism for the demise of these vortices; liquid crystal studies have documented the transient surface heat transfer behavior. Recent examinations of a turbulent approach flow reveal similar types of necklace-type vortex behavior, with a dominant necklace or horseshoe-shaped vortex moving chaotically in the leading edge region. PIV studies show that this vortex undergoes very strong surface interactions, which creates strongly focused "eruptions" of surface fluid, which in turn strongly influence local surface heat transfer. Examinations of the complex processes of the turbulent heat transfer processes using PIV and thermochromic liquid crystal evaluations have show a direct correlation between the eruptive processes and local regions of high heat transfer.

Accomplishments/New Findings

(1) The development of a laminar boundary layer upstream of both two and three-dimensional obstacles mounted on a plane wall was studied. It has been shown that the boundary layer upstream of the obstacle develops initially independently from that on the obstacle itself when the motion is impulsively started from rest. Numerical solutions for the unsteady boundary layer were obtained in both Eulerian and Lagrangian coordinates. It has been demonstrated that in both types of situations, the flow focuses into a narrow band eruption, which is characteristic of separation phenomenon at

high Reynolds numbers. For three-dimensional obstacles, results are obtained on the symmetry plane upstream of the obstacle. These indicate the persistent evolution and subsequent sharp compression of a spiral vortex in the near-wall flow in a manner consistent with the experimental observations. The eruptive response of the two-dimensional boundary layer is found to be considerably stronger than corresponding events in three dimensions. Computed results for the temperature distribution in situations where the wall temperature is constant, but different from that of the mainstream, show that a concentrated response develops in the surface heat transfer. This response is in relative motion as the boundary layer starts to separate from the surface, thereby suggesting that end-wall boundary layers are generally regions of high thermal stress.

(2) Initial analysis of the outboard boundary layer on the end-wall for three-dimensional objects was done. Theoretical developments indicate a complex interaction between the boundary layers on the end-wall and those on the obstacle itself. This interaction acts to sustain the complex vortex system, which develops and surrounds the three-dimensional obstacle.

(3) A detailed set of calculations for a three-dimensional vortex-induced flow was carried out using both spectral and finite-difference methods. The results indicated a variety of complex phenomena that occur as the Reynolds number is increased; these effects are associated with reversed flow in the cross-flow plane and lead to breakup and a new instability of the cross-flow motion. It has been demonstrated that these events are too complex to be resolved using spectral techniques and involve sharply focused behavior in space. In the streamwise direction, behavior similar to wall-layer streaks develop in a manner consistent with that observed in turbulent boundary layers.

(4) Experimentally, the development and translation of the necklace vortices for an impinging laminar boundary layer have been shown to have a profound effect on surface heat transfer, with increases of up to 400% over comparable flat plate values in the absence of the bluff body, with local cyclical variations on the order of ±30%–50%. These increases are the result of the modifying effects of the necklace vortices, particularly a resident corner vortex; the significant cyclical fluctuations are directly tied to the periodic formation and translation of the necklace vortices toward the body. PIV studies indicate the development of strong vortex-surface interactions which result in the concentration and ejection of local boundary layer fluid from the surface, and which subsequently interact with the generating vortex to decrease its strength, and control the vorticity balance in the end-wall region. These fluid ejections are also the primary stimulus for elevation of the surface heat transfer, providing ejection of warm fluid away from the surface, which is replaced by cooler fluid from the surrounding environment.

(5) With an impinging turbulent boundary layer, a large, resident horseshoe-type vortex is observed to move chaotically within an envelope adjacent to the junction, precipitating violent eruptions of wall layer fluid upon close approach to the surface. PIV studies illustrate that these eruptions are similar to those observed for the laminar approach, but more sporadic and much more focused. The chaotic motion of the vortex is caused by intermittent induced vortex behavior due to coalescence of the horseshoe vortex with both vorticity in the impinging boundary layer and with the vorticity from the wall-layer eruptions. The surface heat transfer shows strong local variations, progressing from cross-stream undulations (due to the low-speed streak behavior in the impinging boundary layer) to strong circumferential variations in the junction region. These circumferential variations are a consequence of the surface interaction of the resident horseshoe vortex, and increase local heat transfer by as much as 300% relative to turbulent flat plate values. The combination of the chaotic motion and surface interaction of the horseshoe vortex create sharp temporal variations of up to ±50% in local surface heat transfer, which suggests the importance of the vortex behavior in creating local "hot spots" in comparable turbine blade junctions.

Contract Information

Personnel Supported

J.D.A. Walker (Co-Principal Investigator)
C.R. Smith (Co-Principal Investigator)
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T.L. Praisner (Graduate Research Assistant)
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D.S. Sabatio (Graduate Research Assistant)
L. Takmaz (Graduate Research Assistant)
C.N. Zhikharev (Graduate Research Assistant)

Publications

Doligalski, T.L., Smith C.R. and Walker, J.D.A. 1994 "Vortex Interaction with Walls", *Annual Review of Fluid Mechanics* **26**, 574-616.

Puhak, R., Degani, A.T. and Walker, J.D.A. 1994 "Separation and Heat Transfer of Obstacles", in Advances in Analytical Methods in Modeling of Aerodynamic Flows, J.D.A. Walker, M. Barnett and F.T. Smith (eds.), AIAA..

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Cassel, K., Ruban, A.I. and Walker, J.D.A. 1996 "The Influence of Wall Cooling on Hypersonic Boundary-Layer Separation and Stability", *Journal of Fluid Mechanics* **321**, 189-216.

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Seal, C.V. 1997 "The Control of Junction Flows," Ph.D. Thesis, Lehigh University, May 1997.

Brinckman, K.W. and Walker, J.D.A. 1997 "Breakup and Instability in a High Reynolds Number Flow", AIAA Paper 96-2156; to be submitted to *Journal of Fluid Mechanics*.

Seal, C.V. and Smith, C.R. 1997 "Intertwining Laminar Necklace Vortices," *Physics of Fluids* (Gallery of Fluid Motion) (in press).

Smith, C.R. and Walker, J.D.A. 1997 "Sustaining Mechanisms of Turbulent Boundary Layers: The Role of Vortex Development and Interactions," in Self-Sustaining Mechanisms of Wall Turbulence, R.L. Panton, ed., Computational Mechanics Publications, Southampton, U.K. (to appear).

Interactions/Transitions

a. Meetings

Seal, C.V. and Smith, C.R. "Quantitative Characteristics of a Laminar, Unsteady Necklace Vortex System at a Rectangular Block-Flat Plate Juncture," 47th Meeting of American Physical Society, Atlanta, GA, 21 Nov., 1994.

Takmaz, L. and Smith, C.R. "Experimental Investigation of the Influence of Vortex Interaction on Surface Heat Transfer in End-Wall Boundary Layers," 47th Meeting of American Physical Society, Atlanta, GA, 22 Nov., 1994.

Walker, J.D.A. "Turbulent Wall Layer Vortices", Invited Speaker at Naval Underseas Warfare Center, Newport News, Rhode Island, April 15, 1994.

Walker, J.D.A. "Vortex Interactions with Walls", Invited Keynote Speaker, 3rd Army Research Office Workshop on Rotational Aerodynamics, Georgia Institute of Technology, March 24-25, 1994.

Smith, C.R. "Flow Structure and Heat Transfer in End-Wall Boundary Layers: A Study in Complex Vortex Dynamics," Invited Seminar, Department of Mechanical Engineering, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland, 20 Feb., 1995.

Smith, C.R. "Coherent Flow Structures in Smooth/Flat Bed Turbulent Boundary Layers," Keynote Address at Conference on Coherent Flow Structures in Open Channels: Origins, Scales, and Interactions with Sediment Transport and Bed Morphology, Leeds, England, 10 April, 1995.

Smith, C.R. "Fluid Dynamics and Heat Transfer in End-Wall Boundary Layers," AFOSR Contractors Meeting, Wright Patterson AFB, Dayton, OH, 15 May 1995.

Smith, C.R. "Coherent Flow Structures in Turbulent Boundary Layers: Facts, Hypothesis, Speculation," Invited Seminar, NASA Langley Flow Physics Branch, Langley, VA., 17 July, 1995.

Walker, J. D. A. "Unsteady Boundary-Layer Separation", Invited Seminar, City College, New York, October 3, 1995.

Walker, J. D. A. "Breakup and Instability in a High Reynolds Number Flow", AIAA Paper 96-2156, 1st Theoretical Fluid Mechanics Conference, New Orleans, June, 1996.

Sabatino, D.S., Praisner, T.L., and Smith, C.R. "Simultaneous Measurement of Flow Field Velocity and Surface Heat Transfer," 49th Meeting of American Physical Society, Syracuse, NY, 22 Nov., 1996.

Seal, C.V. and Smith, C.R. "Spatially-Limited Suction as a Means to Control Turbulent Junction Flows," 49th Meeting of American Physical Society, Syracuse, NY, 22 Nov., 1996.

Praisner, T.L., Sabatino, D.S. and Smith, C.R. " An Experimental Investigation of the Simultaneous Flow Field/Heat Transfer Behavior in a Turbulent Juncture Flow," 49th Meeting of American Physical Socoiety, Syracuse, NY, 22 Nov., 1996.

Fitzgerald, J.P. and Smith, C.R. "Experimental Measurement of Deformation and Motion of a Flexible Panel via Shadow Moiré Technique," 49th Meeting of American Physical Society, Syracuse, NY, 22 Nov., 1996.

b. Consultative/Advisory

Smith, C.R. Consultant, Flow Physics Branch, NASA Langley. 17-19 July 1995. Consultation on noise generation by vortices, and turbulent flow structure. Contact persons: Barry Lazos, Bart Singer, Tom Gatski.

New Discoveries, Inventions or Patent Disclosures

None

Honors/Awards

Honor/Award: Fellow, American Physical Society — Year Received: 1991
Honor/Award Recipient(s): J. David A. Walker
Awarding Organization: American Physical Society

Honor/Award: Associate Fellow, AIAA — Year Received: 1993
Honor/Award Recipient: J. David A. Walker
Awarding Organization: American Institute of Aeronautics and Astronautics

Honor/Award: Alexander von Humboldt Senior Scientist — Year Received: 1994
Honor/Award Recipient: J. David A. Walker
Awarding Organization: Alexander von Humboldt Foundation

Honor/Award: Chairman, AIAA Fluid Dynamics Technical Committee — Year Received: 1993-1996
Honor/Award Recipient: J. David A. Walker
Awarding Organization: American Institute of Aeronautics and Astronautics

Honor/Award: Keynote Speaker, Conference on Coherent Flow Structures in Open Channels — Year Received: 1995
Honor/Award Recipient: C.R. Smith
Awarding Organization: British Sedimentological Research Group